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MODELING OF THERMAL PROCESSES IN THE PACKING OF REGENERATIVE HEAT EXCHANGERS IN INDUSTRIAL GLASS-MELTING FURNACES

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A mathematical model of regenerative heat exchangers (regenerators) with stationary refractory packing used for heating incoming air for combustion in the high-temperature melting units of glass works is examined. The calculation package developed with the model can be used to model operation of the regenerators in tank glass-melting furnaces using modern types of packing with a different packing chamber configuration for glass-melting furnaces with horseshoe and transverse flames in consideration of the features of their operation.

The fuel constituent in the total costs in production of glass articles is one of the largest items in the current expenses of enterprises in the glass industry. Consumption of power for production of glass melt even in modern units is 3.35 – 9.50 GJ/ton as a function of the kind of items manufactured and the type of furnace. The specific costs of material and energy resources in glass works in CIS countries are much higher than the same indexes in industrialized countries [1, 2]. One effective direction in conserving power in glass works together with boosting thermal processes is improving the heat engineering equipment, including regenerators with stationary refractory packing that utilize the thermal potential of combustion products for heating the air fed in for combustion [3].

Selecting the energy source and method of regenerating the heat of exiting stack gases is determining for furnace design. Regenerative tank glass-melting furnaces with horseshoe and transverse flames have been widely used for production of glass containers and high-quality glass [2]. They are characterized by a higher heating temperature level for the air entering for combustion in comparison to the recovery units, which boosts glass melting processes. The rational use of refractories and optimum packing designs for the regenerators in glass furnaces are examined in [3, 4]. The effectiveness of using multistage combined packing was demonstrated in [5].

However, the glass furnace regenerator designs were executed with a simplified method based on determination of the average values of the heat transfer coefficients during operation of the regenerator with the equation of E. M. Gol'dfarb and I. D. Semikin. This method does not allow determining the dynamics of the change in the temperatures of the heat-transfer agents and packing refractories in time and over the height of the regenerator packing chamber.

The increase in the efficiency of mathematical modeling is related to developing universal mathematical models which take into account a large number of factors that affect the course of working processes in an object. In the given case, regenerator design using numerical methods obtained by the combined solution of differential transfer equations in heat-transfer agent streams and thermal conduction of the packing with boundary conditions of the third kind is more accurate. The system of differential equations describing heat exchange in the packing of a regenerator usually includes: equations of the thermal conduction of the packing in the gas and air periods; the conditions of heat exchange on the outer surface of the packing; an equation of heat exchange on the interface of the heat-transfer agent stream and the packing; equations of motion of the medium in the gas and air periods; periodicity equations characterizing operation of the regenerator. The conditions characterizing the parameters of the heat-transfer agent entering the packing must also be defined.

Solving such a system of equations is a relatively complicated mathematical problem, so that many simplifications are used in the calculations in practice. Breaking up the packing with a small step over height Δh allows obtaining relatively accurate values of the change in the temperature over the height, not considering the heat flow in the direction of axis z in the model. Nonuniformity of the temperature over

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the thickness of the packing is taken into account by introducing the corresponding correction in calculating the heat exchange coefficients. Finite-difference methods are relatively convenient for practical use as relatively high accuracy of the calculations can be obtained with a large number of steps. These methods include the method of elementary heat balances. The system of differential equations characterizing heat exchange processes in regenerator packing is replaced by a system of algebraic equations in this case.

Solution of the problem by the elementary heat balance method is based on use of the fundamental law of conservation of energy, where the amount of heat entering the elementary volume is equal to the change in the internal energy of a substance. The correlation between the distribution of heat in the space and the heat flow values can be determined with the Newton – Richman and Fourier laws. The amount of heat entering the design element is:

$$Q_\Sigma = Q_{1\mathrm{h}} + Q_\mathrm{s} + Q_{2\mathrm{h}},$$

where Q_s is the amount of heat passing through side surface H_s; $Q_{1\mathrm{h}}$, $Q_{2\mathrm{h}}$ are the amount of heat transferred to heat conduction from the previous to the next element through surface H_h.

The values of heat-exchange surfaces H_h and H_s are determined as a function of the type of packing used.

The temperature of each element examined at the calculated time $(j + 1)$ can be found by solving the heat balance equation:

$$\theta_{i,j+1} = \frac{\theta_{i,j}}{V_i^\mathrm{p}\, c_i^\mathrm{p}\, \rho_i^\mathrm{p}}\left[V_i^\mathrm{p}\, c_i^\mathrm{p}\, \rho_i^\mathrm{p} - \alpha_{\Sigma i,j} H_\mathrm{s} \Delta\tau\right] + \frac{1}{V_i^\mathrm{p}\, c_i^\mathrm{p}\, \rho_i^\mathrm{p}}\left[\alpha_{\Sigma i,j} H_\mathrm{s} \Delta\tau\, \theta_{i,j}^\mathrm{g} - \frac{\lambda_i H_\mathrm{h} \Delta\tau\, \theta_{i-1,j}}{\Delta h} + \frac{\lambda_i H_\mathrm{h} \Delta\tau\, \theta_{i+1,j}}{\Delta h}\right], \quad (1)$$

where i, j are the step over the packing height and time; $\theta_{i,j}^\mathrm{g}$ is the temperature of the stack gases in the calculated section at time j; $\theta_{i,j}$ is the temperature of the calculated element at the current time; V_i^p is the volume of the element; λ_i, c_i^p, and ρ_i^p are the thermal conduction, heat capacity, and density of the packing; $\alpha_{\Sigma i,j}$ is the total heat-exchange coefficient (in the gas period, it is determined as the sum of the coefficients of radiant α_r and convective α_c heat exchange, and in the air period it is set equal to α_c); $\Delta\tau$ is the duration of the period.

In Eq. (1), the thermophysical properties of refractories and heat-transfer agents are determined with consideration of their dependence on the temperature.

We find the temperature of the element in the air period of operation of the heat exchanger similarly. The conditions of heat exchange for the first and last elements will differ from the others, which is taken into account in the corresponding equations. Balance relations in heating and cooling the packing are used for determining the temperature of the heat-transfer agent in the calculation element, and the values of the temperature of the heat-transfer agent for the next calculation segment are found with them. The calculated dependence for stack gases in the packing heating period is:

$$\theta_{i+1,j}^\mathrm{g} = \theta_{i,j}^\mathrm{g} - \frac{V_i^\mathrm{p}\, c_i^\mathrm{p}\, \rho_i^\mathrm{p}(\theta_{i,j} - \theta_{i,j-1})}{M^\mathrm{g} C^\mathrm{g} \Delta\tau},$$

where M^g is the mass flow rate of the stack gases; C^g is the mass heat capacity of the stack gases at temperature $\theta_{i,j}^\mathrm{g}$.

The temperature distribution over the height of the packing, which is selected closest to the steady state if possible, is defined first. The packing is broken down into n elements with step Δh. To ensure the accuracy of the calculated data, it is necessary to correctly select the step with respect to time $\Delta\tau$. The nonuniformity of the temperature field over the thickness of the packing is taken into account by introducing a massiveness coefficient. In designing regenerators, a relatively large number of packing heating-cooling cycles was checked. The distribution obtained at the end of each period was used as the initial distribution for the next period. The calculation was conducted until the difference in the temperature distribution in two neighboring cycles had almost the assigned accuracy. The condition of checking the regenerator output in the quasistationary mode is determined with the equation $\Delta Q_\mathrm{c} \le \Delta Q_\mathrm{cur}$, where the current error is calculated with the values of temperature t of the packing in two cycles:

$$\Delta Q_\mathrm{cur} = V_i C_i^\mathrm{p} \rho_i^\mathrm{p}\,(t_{i,j+1} - t_{i,j}). \quad (2)$$

When condition (2) is not satisfied, the calculation is continued until the assigned and obtained errors coincide. The mathematical model of heat exchange in regenerators with stationary packing is examined in more detail in [6].

The mathematical model described was used to develop a method for creating a computer package for investigating the work of regenerators with different configuration decisions [7] (see flow chart in Fig. 1). The software package consists of separate logically structural blocks that describe the correlation of the thermal processes that take place in the heat-retaining elements of the packing with operation of the basic unit, which ensues efficient functioning of the entire program as a whole. The computer package is for modeling the operation of furnace regenerative heat exchangers with different configurations, including transverse and horseshoe flames in the melting zone.

Sectional regenerators positioned along the side walls of the furnace are used in glass-melting furnaces with transverse flame direction. A special feature of the operation of such heat exchangers is that the flows of stack gases $V_{\mathrm{g}i}$,

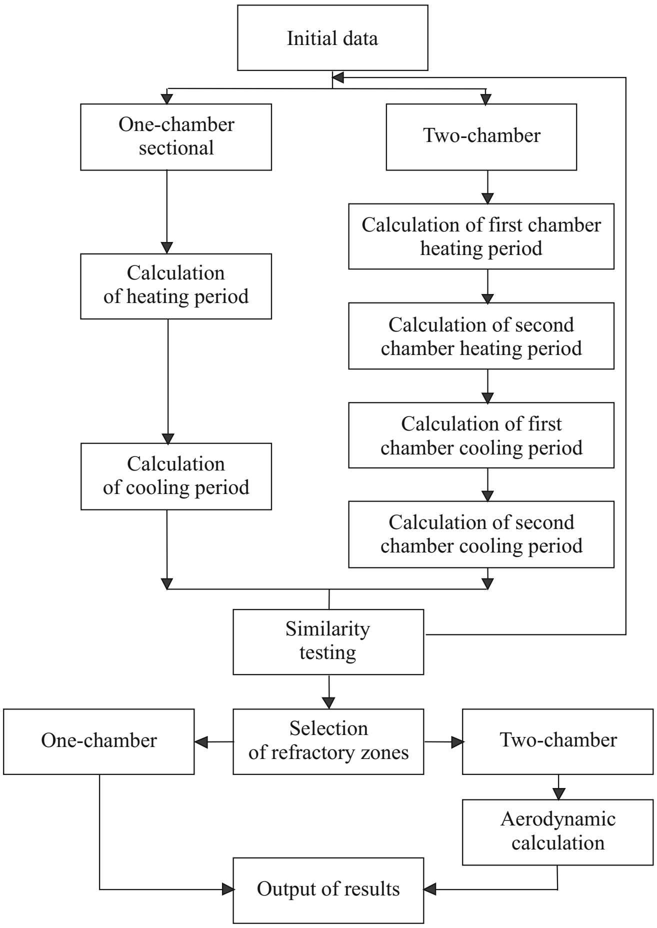

Fig. 1. Flow chart of the calculation package for designing regenerators in industrial glass-melting furnaces.

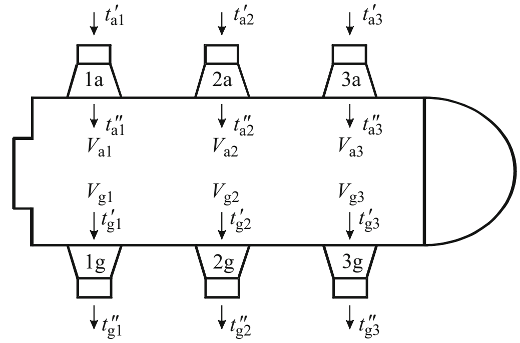

Fig. 2. Diagram of a glass-melting furnace with transverse flame direction and sectional regenerators: 1a – 3a) regenerators operating in the air heating mode; 1g – 3g) regenerators operating in the stack gas cooling mode.

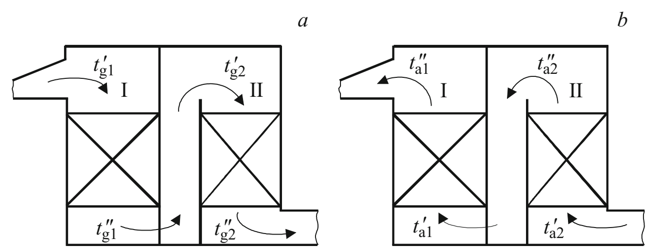

Fig. 3. Diagram of a two-chamber regenerator: *a*) heating period; *b*) cooling period.

heated air V_{ai}, and the temperature of the stack gases at entry t'_g are different for each section.

The diagram of a flow-through glass melting furnace with a transverse flame and specific output of 0.265 tons/(m^2 · day) is shown in Fig. 2. The furnace is equipped with three sectional regenerators with 120 mm Lichte packing. The temperature of the air entering the heat exchanger is 50°C. The results of calculating the glass-melting furnace are reported in Table 1.

The thermal work of sectional regenerators in furnaces with a transverse flame direction can thus be modeled with the developed software package with consideration of the characteristic features of their operation. This allows using it for designing or revamping glass-melting furnaces of the given type widely used in glass works.

The regenerators in horseshoe flame furnaces are positioned behind the end wall of the furnace.

Let us examine a regenerative furnace with a horseshoe flame and specific output in glass melt of 0.508 tons/(m^2 · day). The volume of the regenerator's packing chamber is 9.95 m^3, and the Lichte packing channel size is 160 mm. The temperature of the stack gases entering the packing is set at 1250°C and the air temperature is 100°C. As the calculations showed, the average air heating temperature was 860°C.

One method of increasing the temperature of the air for combustion is to increase the volume of the regenerator's packing chamber. However, increasing the length of the regenerator packing chamber makes the flow rate of the heat-transfer agent uneven over the section of the packing. For this reason, in the given case, it is expedient to use two-

TABLE 1

Section	Flow rate, m^3/sec		Temperature of stack gases entering heat exchanger t'_g, °C	Average temperature per cycle, °C		Amount of heat transferred per cycle Q_a, MJ/cycle
	stack gases	air		gases $\bar{t}_g$	air $\bar{t}_a$	
1	0.6881	0.6254	1250	551	920	1375.2
2	0.7497	0.6815	1290	579	939	1533.4
3	0.6162	0.5601	1225	525	917	1227.8

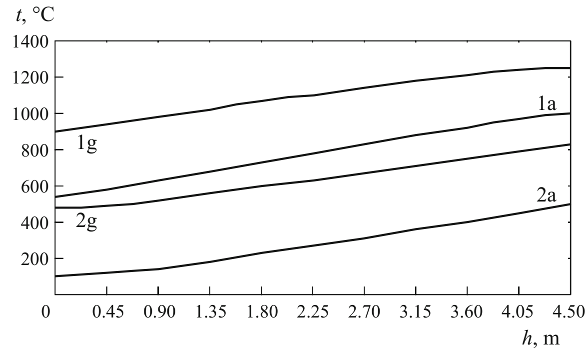

Fig. 4. Temperature distribution *t* of heat-transfer agents over height *h* of regenerator packing chambers: *1*) hot chamber; *2*) cold chamber; g) stack gases; a) air.

chamber regenerators (Fig. 3). This makes it possible to significantly increase the heat-exchange surface of the packing, which allows more completely utilizing the thermal potential of the stack gases going out of the furnace.

It was assumed that the first hot chamber of the regenerator is of the same size as before revamping. In view of the dust content of the stack gases, it is more effective to use packing with continuous channels of castable elements of the Topfstein type with a 140 × 140 mm channel size. A dust collection chamber is positioned after the first chamber and the regenerator cold chamber is located farther on. Lichte packing with 120 × 120 mm channel size (50 mm brick width) is used in the second chamber. The temperature distribution of the heat-transfer agents over the height of the packing at the end of the heating and cooling periods is shown in Fig. 4.

The calculations showed that the average air heating temperature with the two-chamber generator increased from 860 to 1015°C and the average temperature of the outgoing stack gases decreased from 661 to 460°C, which increased the efficiency of heat utilization in the glass-melting furnace as a whole.

The mathematical model of the glass-melting furnace regenerator thus makes it possible to model the thermal processes that take place in heat exchangers of this type with a different configuration, including multichamber and sectional regenerators.

The software package developed with the model can be used to determine the temperature distribution of the heat-transfer agents and refractory materials over the height of the packing chamber and the character of the change in it in time when any materials and types of packing are used. The software can be used in designing and revamping regenerators in the melting units of glass works and for solving problems of optimum design and control.

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